第 31 卷 增刊 I 高 能 物 理 与 核 物 理 Vol. 31, Supp. I
2007 年 7 月 HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS Jul., 2007

Status Report of the NSCL/MSU ECR Ion Sources*

P.A. Závodszky[1)] B. Arend D. Cole J. DeKamp M. Doleans G. Machicoane F. Marti
P. Miller J. Moskalik W. Nurnberger J. Ottarson M. Steiner J. Stetson
J. Vincent X. Wu A. Zeller Q. Zhao

(National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA)

Abstract Since the last ECR Workshop, NSCL/MSU has been involved in a vigorous ECR ion source R&D program, which resulted in the construction of an off-line test ECR ion source (ARTEMIS-B) for new beam development and ion optics studies. Also the design and partial completion of a 3rd generation, fully superconducting ECR ion source, SuSI has been accomplished. This paper is an overview of the construction projects and the different R&D activities performed with the existing ion sources. These activities include development of metallic ion beam production methods using evaporation with resistive and inductive ovens and sputtering of very refractory metals. Ion optics developments include testing different focusing elements (magnetic solenoid lens, electrostatic quadrupole triplet lens, Einzel lens, electrostatic double doublet quadrupole combined with an octupole lens), and different beam forming and diagnostics devices. The detailed results will be presented at the workshop in separate talks and posters.

Key words ECR ion sources, highly charged ions, beam optics

1 Introduction

The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) operates two cyclotrons in coupled mode in order to produce radioactive ion beams by projectile fragmentation[1]. The primary beam energy is up to 160MeV/u, and since October 2000 many different primary beams were accelerated between ^{16}O and ^{238}U[2]. The primary ions are produced by two ECR ion sources, one superconducting (SC-ECR) built in the early 90's[3], and the other (ARTEMIS) with room temperature solenoids and permanent magnet hexapole[4] built from a design based on the AECR-U at the Lawrence Berkeley National Laboratory (LBNL)[5].

A vigorous research and development (R&D) program has produced increased primary beam intensities available for radioactive beam production. Fig. 1 shows the evolution of the accelerated beam intensity for several ions in the past two years. Our efforts were concentrated in design and construction of two new ECR ion sources, better beam diagnostics, systematic

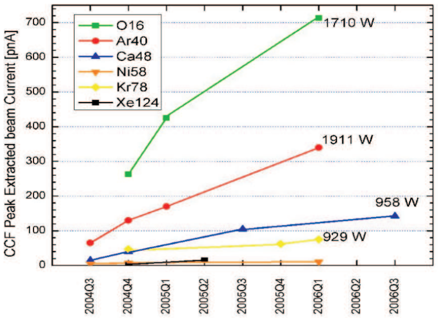

Fig. 1. Peak current extracted (at ~140MeV/u) by quarter years from 2004 3rd quarter to 2006 3rd quarter. The Ar-40 beam reached 2kW beam power in January 2006.

Received 20 April 2007

* Supported by National Science Foundation under grant PHY-0110253

1) E-mail: zavodszky@nscl.msu.edu

studies of different focusing elements after the extraction system of the ion sources and simulations of the whole injection beamline from the ion sources to the K500 cyclotron. Significant effort has been spent on the development of different metallic ion beam production methods.

2 New test ion source construction

Following the recommendation of an Operations Advisory Committee appointed by the National Science Foundation, we built a new off-line ECR ion source during the years 2004—2005 to allow for ion source and beam development in parallel with the nuclear physics experimental program. In order to easily transfer the newly developed hardware and new tuning procedures to the production area, we decided to make an exact copy of ARTEMIS[4], with a similar low energy beamline to the K500 cyclotron injection line. The construction was completed in June 2005 and details were presented in Ref. [6].

In August 2005, the new off-line test source ARTEMIS-B passed the Operational Readiness and Safety Review and ignited the first plasma. After a few weeks of commissioning work, we started a systematic R&D program aimed at improving ion source performance, ion extraction, low-energy beam transport and metallic beam production methods.

3 Ion optics development

In September 2004, the focusing solenoid under the SC-ECRIS was replaced with an electrostatic quadrupole triplet (National Electrostatics Corp. Model EQTS76-15). The bore diameter is 76mm, but to protect the internal elements from direct beam, a 50mm diameter water-cooled aperture was placed at the triplet entrance. This triplet provided significant increases in useable beam to the K500 cyclotron compared to the previous arrangement, which motivated further development[7, 8].

The off-line ECR ion source ARTEMIS-B allows time to study various focusing elements after extraction from the ion source. From November 2005 to May 2006 the performances of a standard focusing solenoid, a large-bore electrostatic triplet (LBT) with a 152mm nominal bore diameter and an electrostatic quadrupole double doublet (DD) were extensively compared. Both the transmission and the emittance of the ion beam were measured, using Faraday cups and an emittance scanner, respectively. In addition, tuning procedures were developed that helped minimize development time when transferring a particular focusing element to operation. The LBT was moved to production in January 2006 and replaced later in June 2006 with the DD on the ARTEMIS-A beamline.

In parallel extensive tests and commissioning of an Allison-type emittance scanner[9] took place. An identical system had been installed previously in the K500 cyclotron injection beamline and the work on ARTEMIS-B helped both to gain experience on emittance data acquisition and a better understanding of the ion beam quality.

The 90° analyzing magnets used both in the test stand and in the production beamline were studied to better understand their beam optics properties. It was found that these magnets have large sextupole aberration terms, a finding supported also by beam optics simulations. In order to minimize the beam quality degradation by this aberration, we installed a 25mm diameter aperture at the entrance of the magnet, with further plans to replace these magnets with a new design, similar to the magnet build by the LBNL group for the VENUS ECR ion source[10].

The details of the hardware and beam optics R&D efforts are presented at this Workshop in Refs. [11] and [12].

4 Metallic ion beam development

A significant part of the NSCL nuclear physics program requires metallic primary ion beams and, in many cases, highly enriched isotopes available in elemental form or as oxides. In order to minimize the amount of chemistry involved in the production of the primary beam and to keep the contamination at a minimum level in the ion sources, our preferred production methods are evaporation from ovens and sputtering with positive ions. The ^{48}Ca beam is produced from calcium metal, obtained in an off-line conversion process from ^{48}CaCO$_3$. We routinely convert calcium with >90% overall efficiency. The use of a tantalum hot screen and an axial resistively- heated oven greatly reduced our consumption rates. In a recent run we managed to accelerate and maintain over several days 100 — 150pnA (1kW) of 140MeV/u ^{48}Ca^{20+} ion beam, exceeding our laboratory's 2008 milestone of 100pnA for this beam.

An inductively heated oven has been used to evaporate Fe, Ni, Ge and U. The first three elements were evaporated from alumina crucibles. For the production of U ion beam, we used UO$_2$ and a crucible made of hafnia (HfO$_2$). This chemical form of uranium has the advantage that is not melted at ~2000℃ necessary for evaporation and does not chemically attack the hafnia crucible. Hafnia is a ceramic material with a melting point of 2817℃, second only to thoria. The quantity of ^{16}O introduced in the plasma chamber by evaporating UO$_2$ was less than the optimum amount of support gas used in the production of the ^{238}U^{30+} ion beam, allowing the use of additional amounts of oxygen as an ion source tuning parameter. This ion beam was also produced by sputtering, obtaining the best yields using argon as support gas. Fig. 2 shows a charge state distribution in the Faraday cup following the 90° analyzing magnet. The results of the sputtering development are presented in a separate contribution to this Workshop[13].

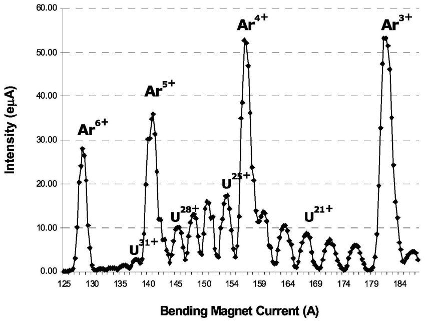

Fig. 2. ^{238}U^{q+} charge state distribution obtained by the sputtering method, using ^{40}Ar as support gas.

5 Status of the SuSI construction project

In order to replace the SC-ECR and substantially improve beam output, in 2004 we initiated a new project to design and build a fully superconducting ECR ion source optimized for 18GHz microwave frequency. We decided to adopt a design that allows flexibility in tuning the intensity and the emittance of the ion beam extracted from the Superconducting Source for Ions (SuSI). We adopted an original approach to change the position of the plasma electrode relative to the resonant zone in the plasma. We will keep the plasma electrode fixed and we will move the axial magnetic field. This can be accomplished with two solenoids at each end of the ion source. In order to have the magnetic field minimum easily adjustable, there will be a third pair of solenoids between the injection and extraction ends, running electric currents in the opposite direction. Each combination of the six solenoids is capable of producing the required magnetic field profile for optimum operation at 18GHz. We call this approach the Flexible Magnetic Field Concept[14].

The length of the plasma chamber, as well as the bias disk and puller electrode positions will be all remotely tuneable, as described in Ref. [15]. To minimize the emittance increase due to the space charge effects before charge state selection, the plasma chamber of SuSI will float at +30kV, the beamline between SuSI and to a location after the analyzing magnet will be biased to −30kV. After charge state selection the beam will be decelerated back to about 30kV∗q as required for injection into the K500 cyclotron.

The SuSI full coil system was tested in a vertical test-dewar early in 2006. After several training quenches, the sextupole coils reached 600 Amps, producing 2T radial field at 50.8mm, the radius of the plasma chamber inner wall. The axial fields reached values of 3.6T and 2.2T at the injection and extraction side, respectively. These values are sufficient for 28GHz microwave frequency operation. During these tests, the magnets operated as predicted when the coils were energized together, showing that a large window is available for tuning. We were not able to reach the operating current value in the hexapole coils when we tried to energize them in the full field of the solenoids. If the radial and axial forces are applied together, the hexapole moves into a stable operating position. If these forces are applied separately, the hexapole undergoes positional changes that initiate a quench, likely through boundary slippage. More details about the construction and testing of the SuSI magnet are given in Ref. [16].

Because the magnets of SuSI were originally designed to work at fields optimised for 18GHz, we decided to redesign the horizontal links of the cryostat in order to support higher loads at fields necessary for 28GHz operations. These new links are made of titanium and are about 3 times stronger than the original fiberglass links. The total calculated additional heat load on the liquid helium vessel due to the new titanium links is about ~2W, acceptable for a magnet filled continuously with liquid helium from the NSCL cryogenic system.

We are currently in the final stages of the cryostat assembly. Fig. 3 shows a photo of the magnet before the end caps of the cryostat were welded. After completing the cryostat, in the period of October – December 2006, we plan to have an extensive commissioning of the magnet, starting the ion source assembly and commissioning in January 2007. In parallel to cryostat assembly, the yoke of the magnet was assembled together with the injection and extraction hardware, plasma chamber and high voltage insulation (see Fig. 4) in order to leak check and test the different subassemblies for high voltage holding.

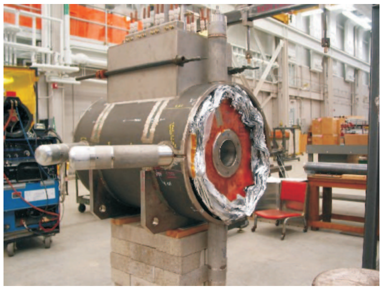

Fig. 3. The SuSI magnet cryostat before the super insulation is applied to the front and back end of the liquid nitrogen thermal shield on September 12, 2006.

Fig. 4. The SuSI magnet yoke with the injection and extraction hardware and plasma chamber with electrical isolation ready for tests, on September 12, 2006.

5.1 SuSI low energy beam transport line

The 90° analyzing magnet fabrication is in progress. The magnet is a slightly modified version of the magnet built by the LBNL ECR group for the VENUS ECR ion source[10]. The main difference between these two magnets is the SuSI analyzing magnet will have a beam chamber electrically isolated from the yoke and pole tips, in order to be able to float the beamline and the magnet beam chamber at a maximum of −30kV.

The deceleration after the analyzing magnet back to ground potential will be accomplished with a three-element Einzel lens. This lens will also compensate for the beam expansion due to deceleration. The first element will be at −30kV (the potential of the beamline between the ion source and the deceleration point after the analyzing magnet), the second electrode will be at an adjustable positive voltage (up to 15kV), and the third element at ground potential, similar to the beamline downstream toward the K500 cyclotron (or the rest of the test beamline).

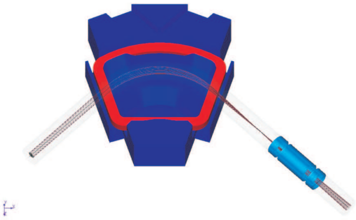

Fig. 5. ^{48}Ca^{8+} ion trajectories through the 90° analyzing magnet and decelerator Einzel lens.

A ^{48}Ca^{8+} ion beam simulation through the 90° analyzing magnet and decelerator Einzel lens is shown in Fig. 5. The initial energy of the ion beam is 480keV (60kV∗q), the final energy is 240keV (30kV∗q). For the simulation we used the Lorentz-3D software package[17].

References

1 Marti F, Miller P, Poe D et al. In Cyclotrons and Their Applications 2001, AIP Conf. Proc., 2001, **600**: 64

2 Miller P, Marti F, Poe D et al. Proc. of the 17th Int. Conf. on Cyclotrons and their Applications, October 18-22, 2004, Tokyo, Japan, (Particle Accelerator Society of Japan, 2005), 62

3 Antaya T A, Gammino S. Rev. Sci. Instr., 1994, **65**: 1723

4 Koivisto H, Cole D, Fredell A et al. Proc. of the Workshop on the Production of Intense Beams of Highly Charged Ions, Catania, Italy, 2000, Italian Physical Society Conference Proceedings, 2001, **72**: 135

5 XIE Z Q, Lyneis C M. Proceedings of the 13th Int. Workshop on ECRIS, Texas A&M Univ., College Station, TX, USA, 16 (1997)

6 Machicoane G, Cole D, Ottarson J et al. Rev. Sci. Instr., 2006, **77**: 03A322

7 Stetson J W, Kazarinov N Y, Machicoane G et al. Proc. of the 17th Int. Conf. on Cyclotrons and their Applications, 2004, Tokyo, Japan, (Particle Accelerator Society of Japan, 2005), 483

8 Stetson J W, Kazarinov N Y, Machicoane G et al. Proc. of the 2005 Particle Accelerator Conference, Knoxville, TN, 2005, (IEEE Publishing, Piscataway, NJ, 2005), 2281

9 Allison P W, Sherman J D, Holtkamp D B. IEEE Trans. on Nucl. Sci. NS-30, 1983. 2204

10 Leitner M, Abbott S R, Leitner D et al. Proc. of the 15th Int. Workshop on ECRIS, Jyväskylä, Finland, (2002)

11 Machicoane G et al. HEP & NP, 2007, **31**(Suppl. Ⅰ): 187 (in Chinese)
(Machicoane G et al. 高能物理与核物理, 2007, **31**(Suppl. Ⅰ): 187)

12 WU X et al. HEP & NP, 2007, **31**(Suppl. Ⅰ): 196 (in Chinese)
(WU X et al. 高能物理与核物理, 2007, **31**(Suppl. Ⅰ): 196)

13 Cole D et al. HEP & NP, 2007, **31**(Suppl. Ⅰ): 239 (in Chinese)
(Cole D et al. 高能物理与核物理, 2007, **31**(Suppl. Ⅰ): 239)

14 Závodszky P A et al. Proc. of the 16th Int. Workshop on ECRIS, Berkeley, CA, USA, AIP Conf. Proc., 2005, **749**: 131

15 Závodszky P A et al. Nucl. Instrum. Methods, 2005, **B241**: 959

16 DeKamp J C et al. Proc. of the 2006 Applied Superconducivity Conference, Seattle, WA, 2006; to be published in IEEE Trans. on Appl. Supercond

17 www.integratedsoft.com